


Critical Materials: Rare Earth & Related Elements

Mark Johnson

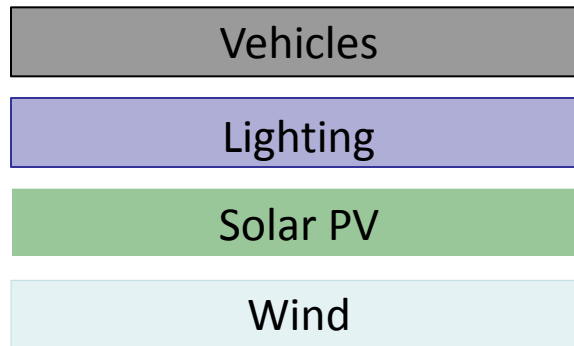
February 28, 2011

Critical Materials in Clean Energy

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3 Li Lithium 6.941	4 Be Beryllium 9.012182																	5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.9984032	10 Ne Neon 20.1797			
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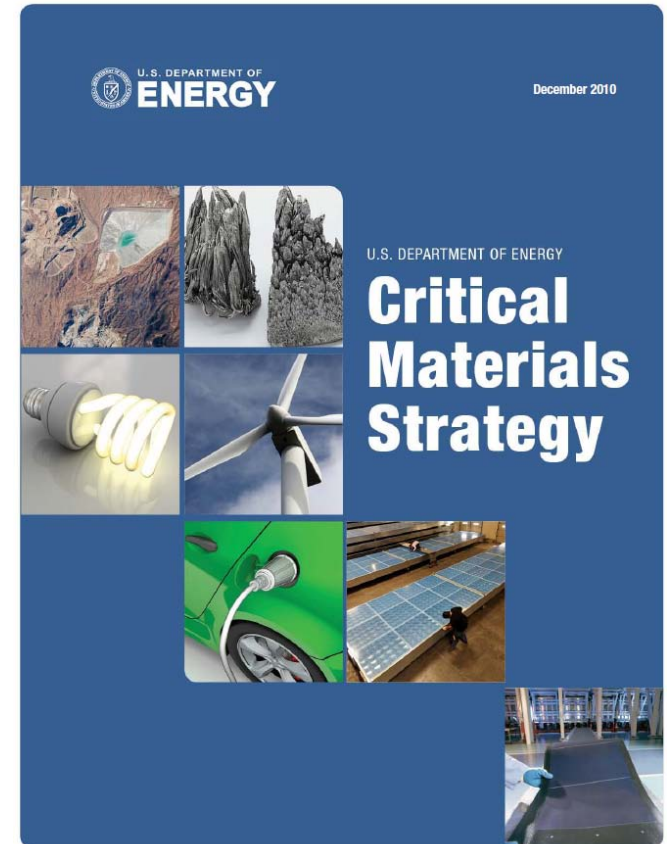


US DOE: Critical Materials
Strategy (Dec 2010)

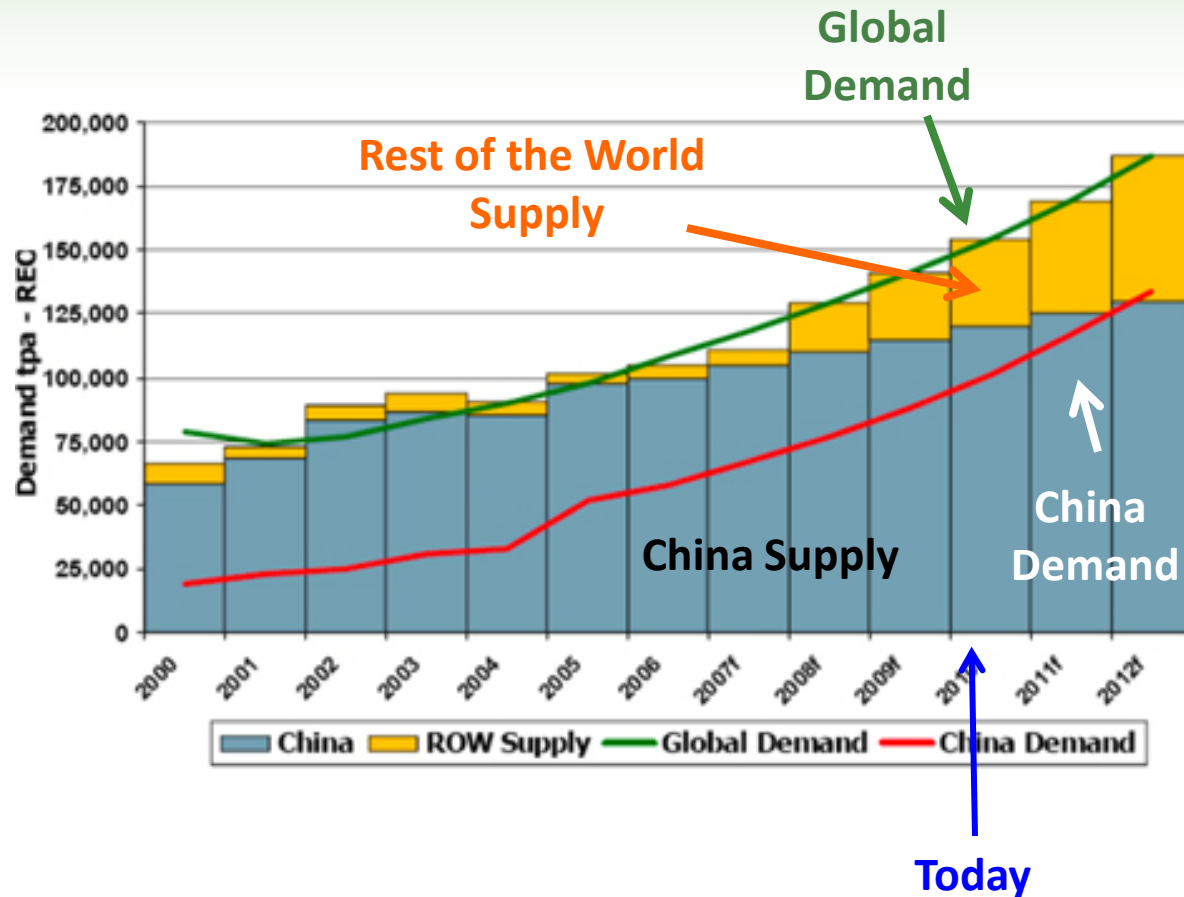


Coordinated Critical Materials Effort

- Policy and International Affairs (PI) led Department-wide Critical Materials Strategy Study
[David Sandalow, Assistant Secretary, PI]
- US-Japan Roundtable (LLNL) on Rare Earths (Nov 2010)
- US-EU Workshop on Rare Earths Research (Dec 2010)
- ARPA-E Workshop on Critical Materials Technology (Dec 2010)



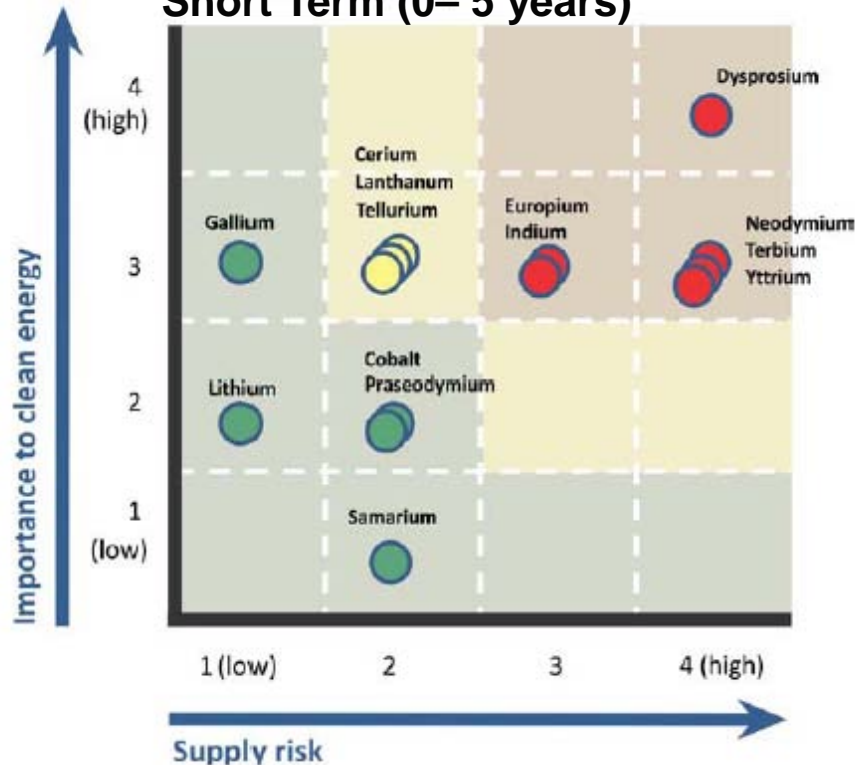
Shifting Economics Of Rare Earth Materials



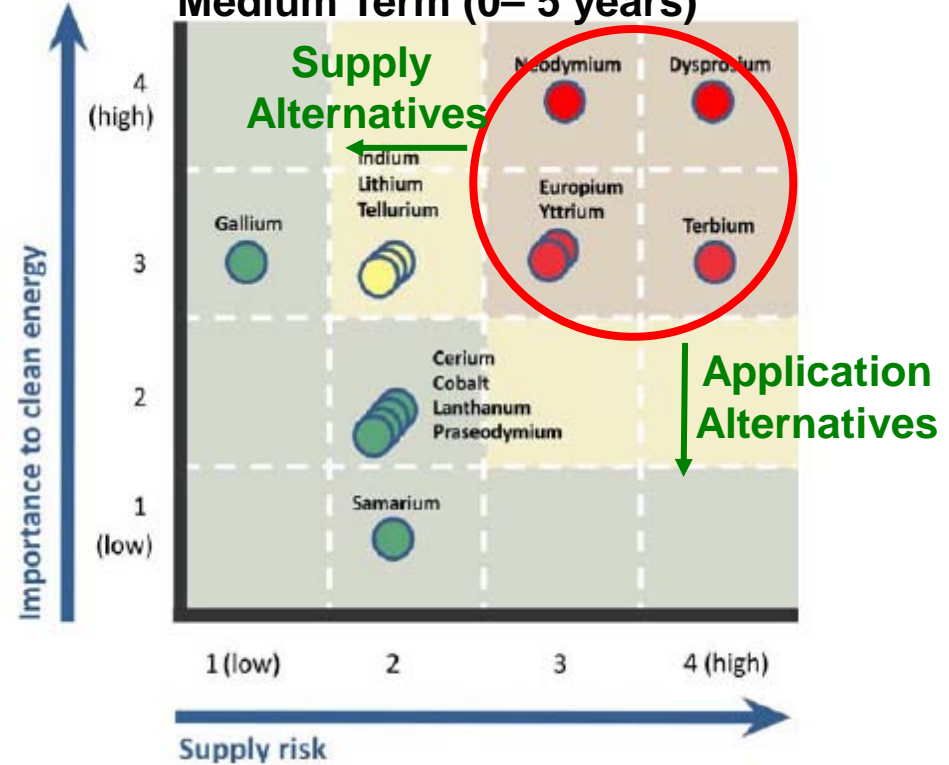
**Within 5 Years: World's Dominant Supplier of Rare Earth Materials
May Switch From a Net Exporter to a Net Importer**

Rare Earth Criticality by Element

Short Term (0– 5 years)



Medium Term (0– 5 years)

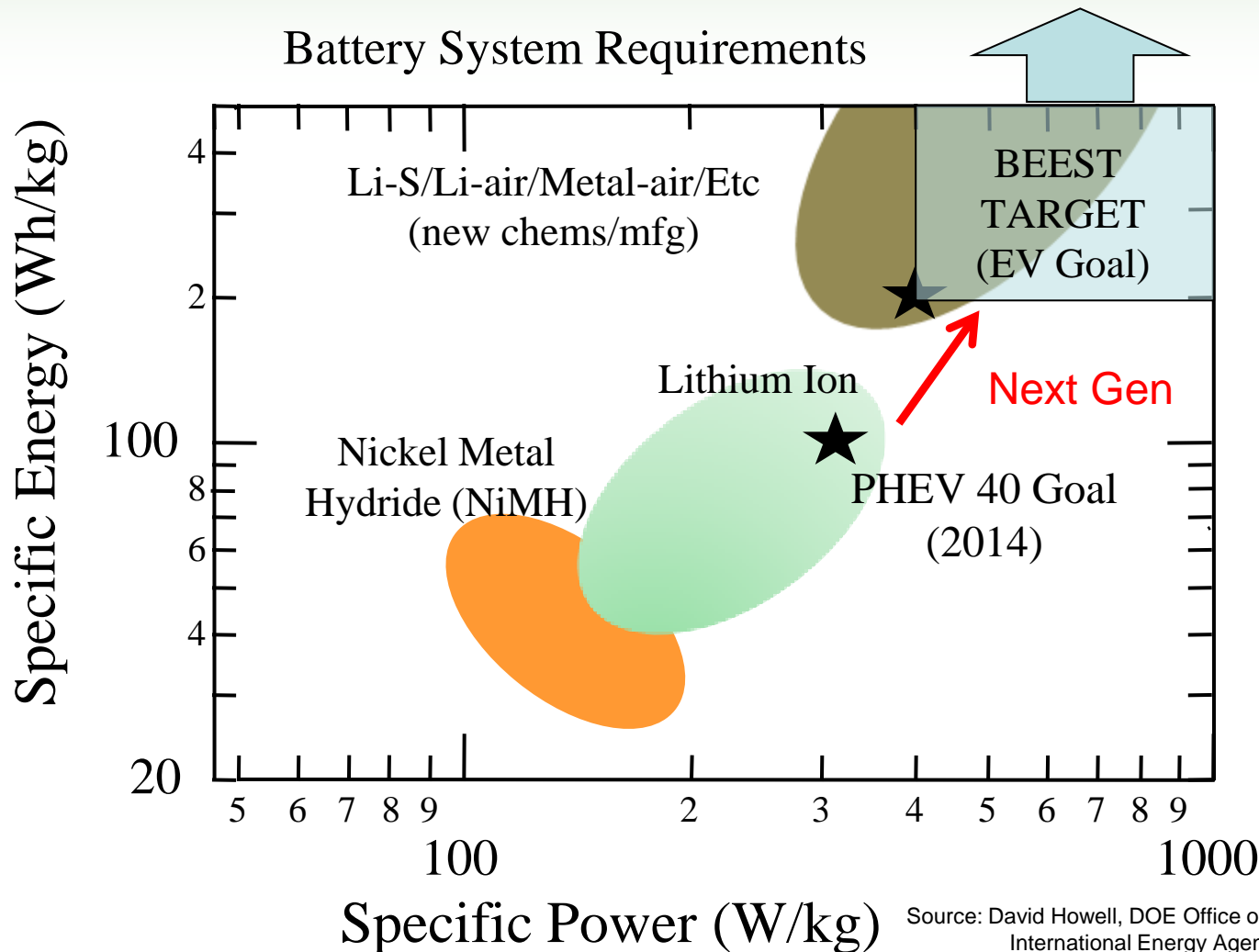


US DOE: Critical Materials Strategy (Dec 2010)

Possible Approach: Eliminate Need for Material

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Batteries for Electrical Energy Storage in Transportation (BEEST) Program



Storage Cost
Current Target:
\$1,000/kWh

BEEST Target:
\$250/kWh

Source: David Howell, DOE Office of Vehicle Technologies, 2009.
International Energy Agency, *Technology Roadmaps:*
Electric and Plug-in Hybrid Electric Vehicles

Possible Approach: Get Most From Available Supply

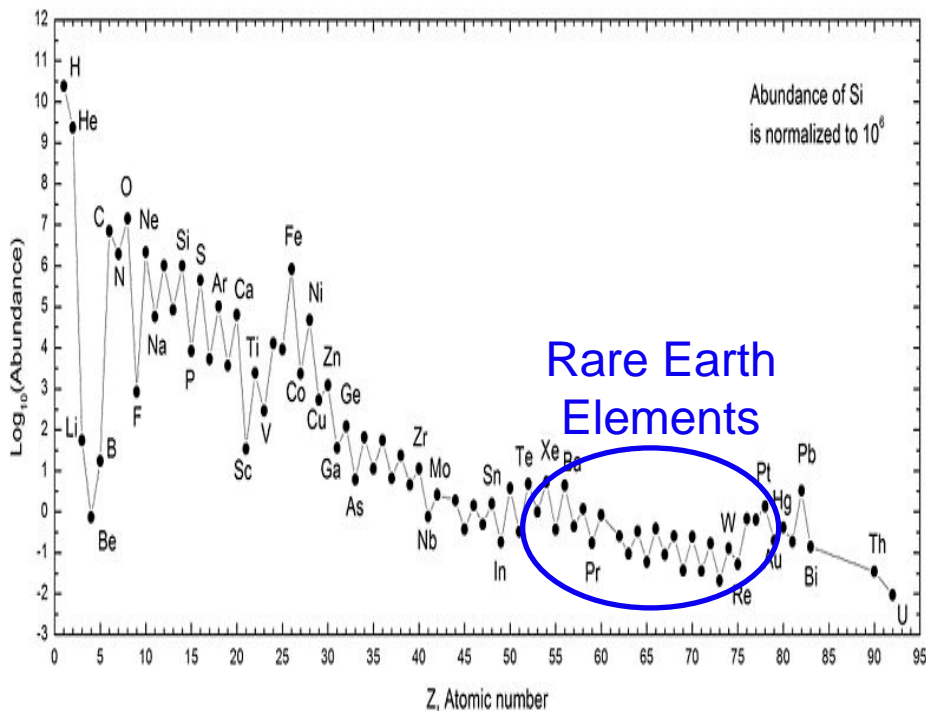
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Light Rare Earth Elements

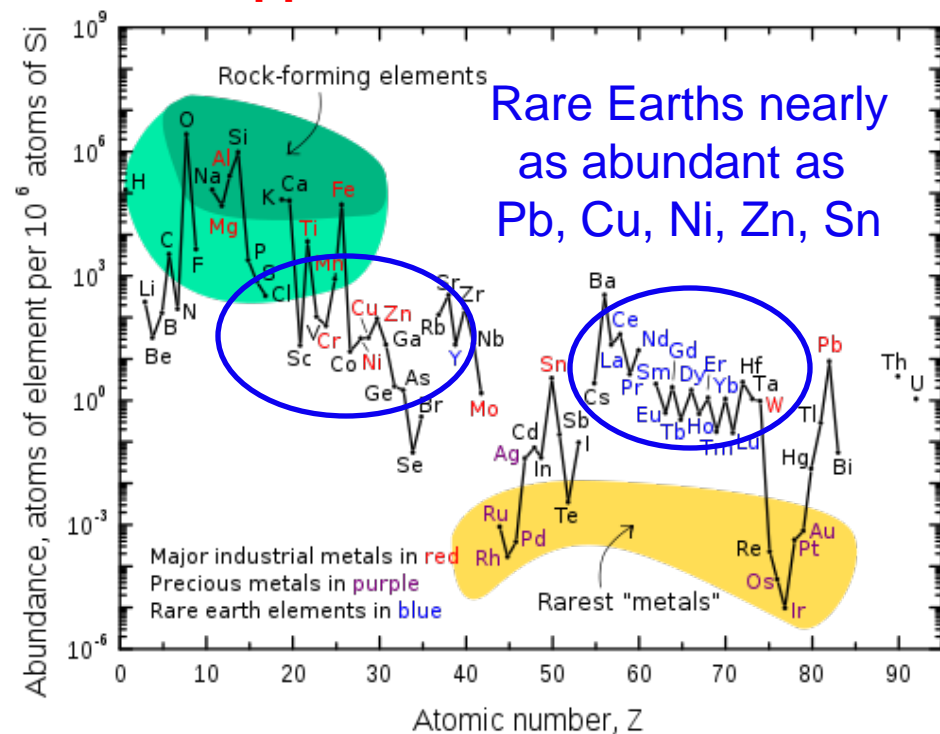
Heavy Rare Earth Elements

Rare Earth Elements Are Not That Rare

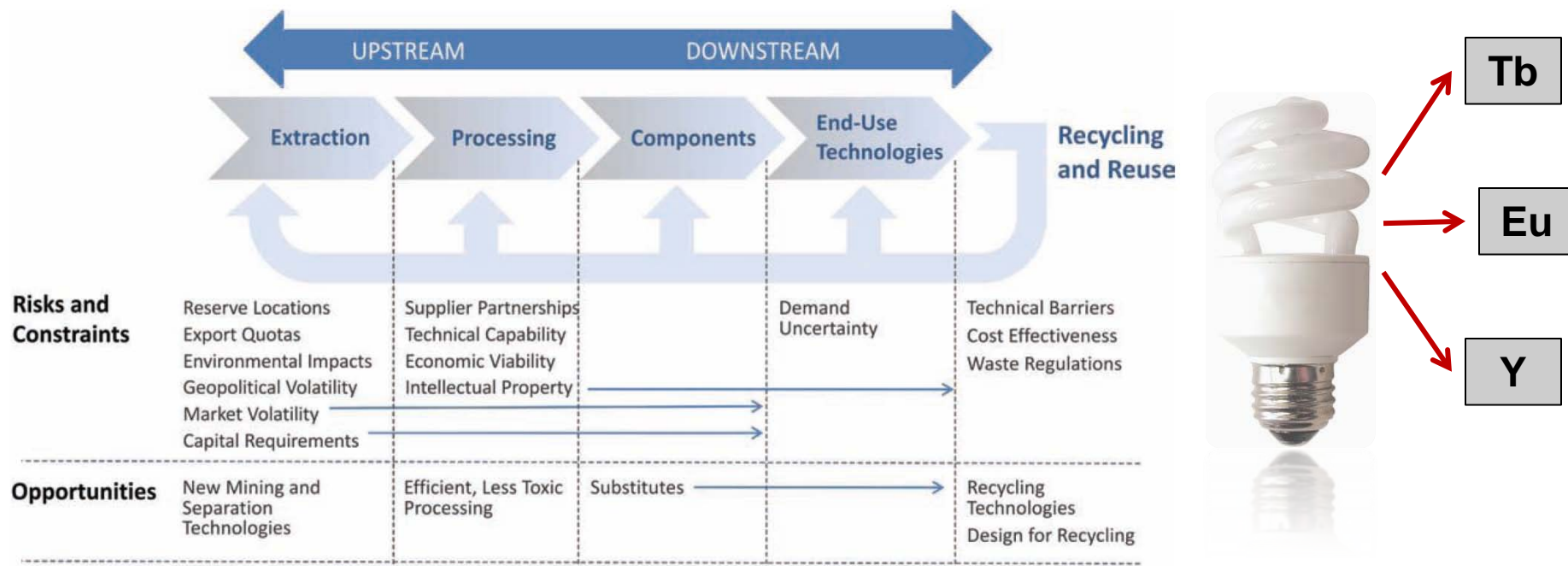
Solar System Abundance



Upper Crust Abundance



Developing Technology Alternatives Across Supply Chain



Critical Materials in Clean Energy from DOE-Wide Study



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Vehicles

Lighting

Solar PV

Wind



Key Elements in Energy-Wide Supply Chain

Traditional Energy

Smart Grid

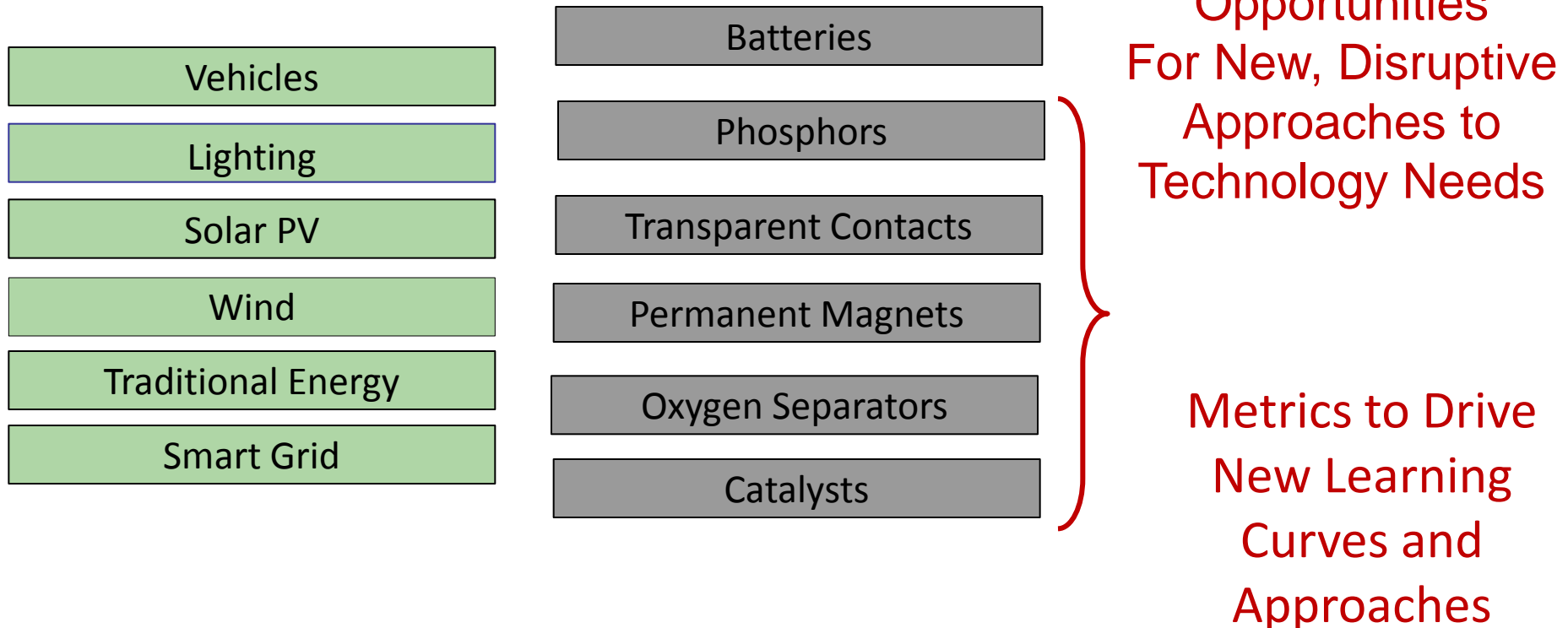
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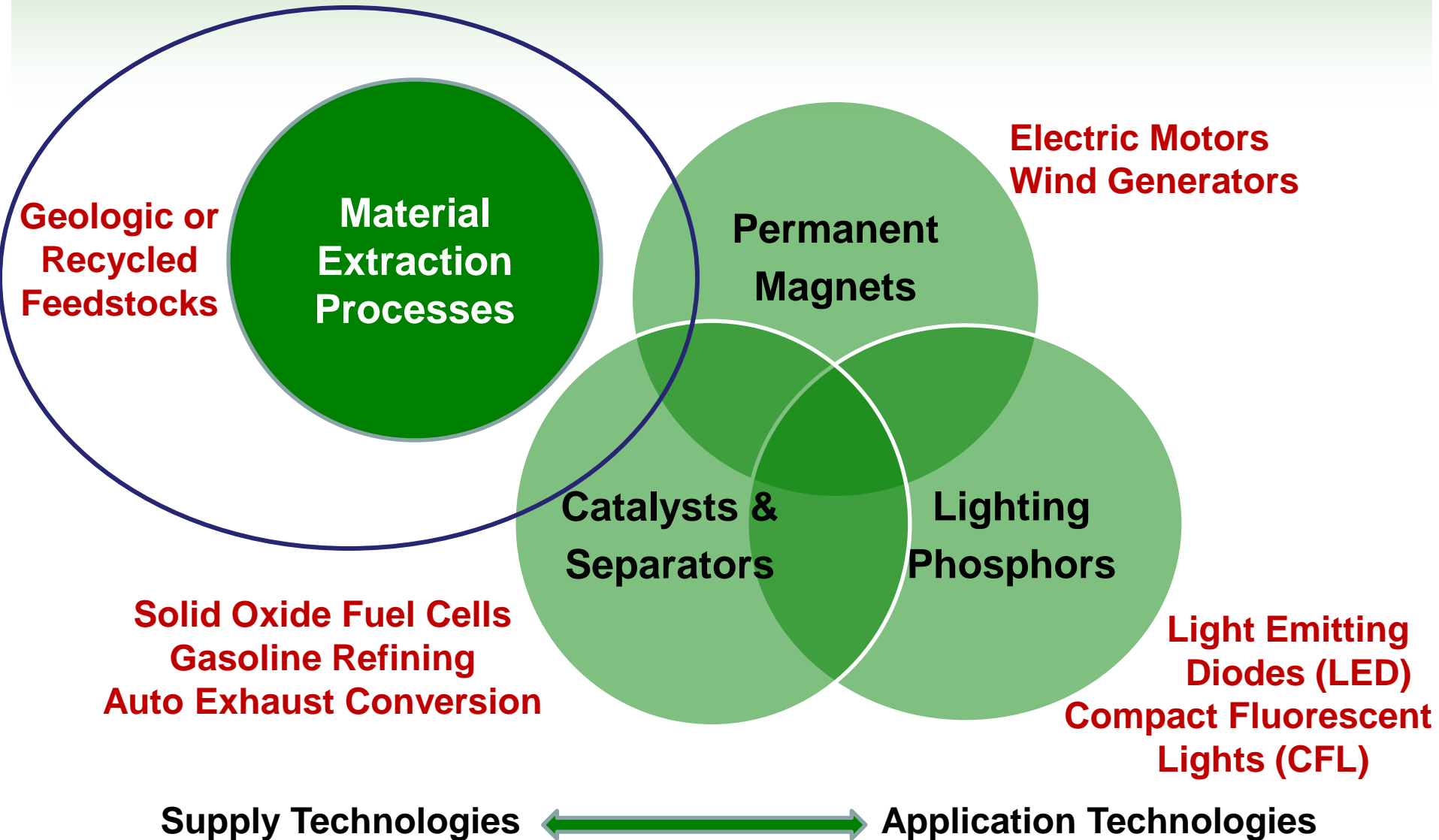
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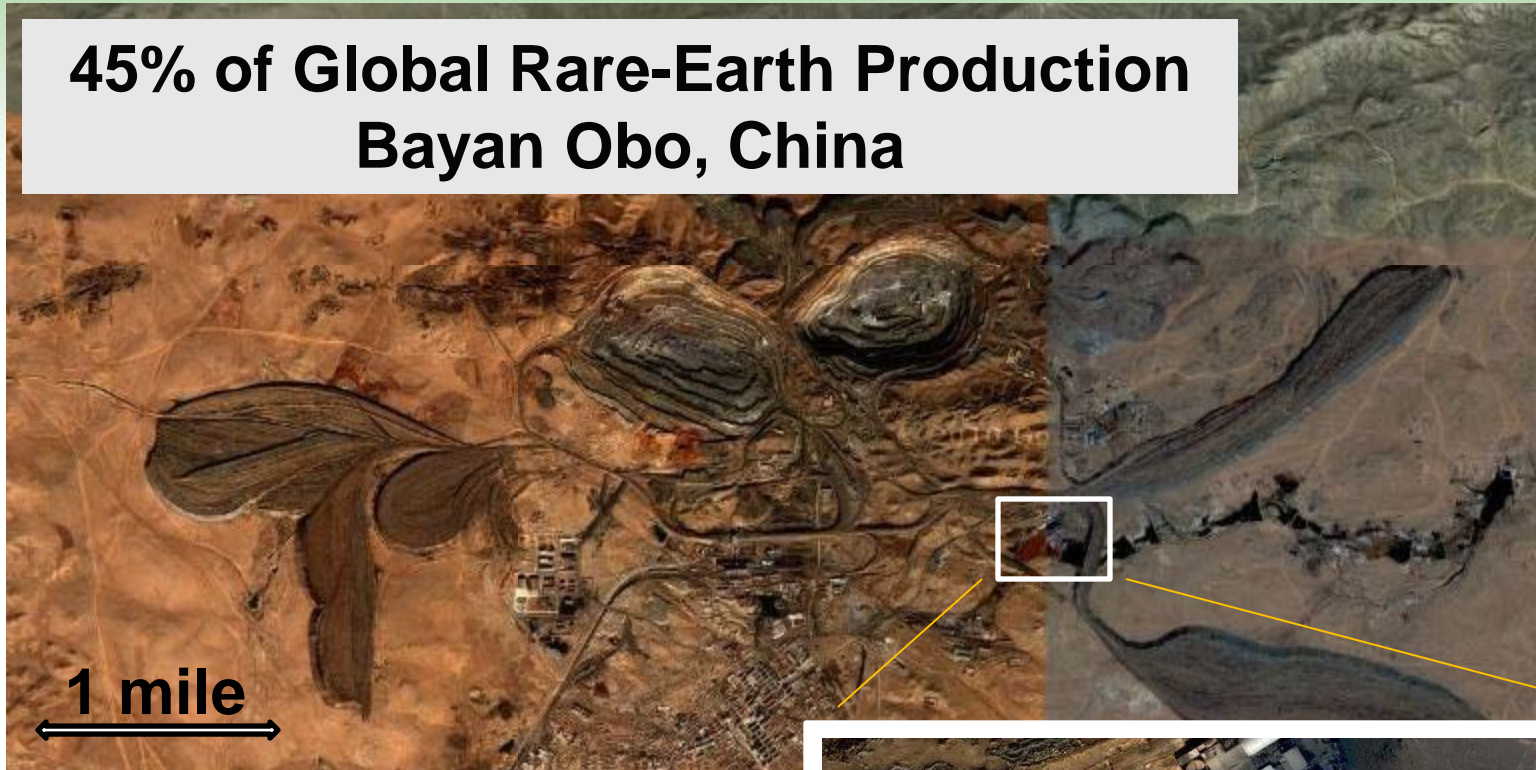
Technology Opportunity Areas for Study



ARPA-E Workshop: Critical Materials Technology



45% of Global Rare-Earth Production Bayan Obo, China



Primary Ore:

Bastnasite: $\text{RE}(\text{CO}_3)\text{F}$
800 million metric tons; 6% REO

Secondary Ore:

Monazite: RE-PO_4

Photos: Google Maps



US Rare-Earth Production Capability Mountain Pass, CA (re-opened by Molycorp)



Primary Ore:

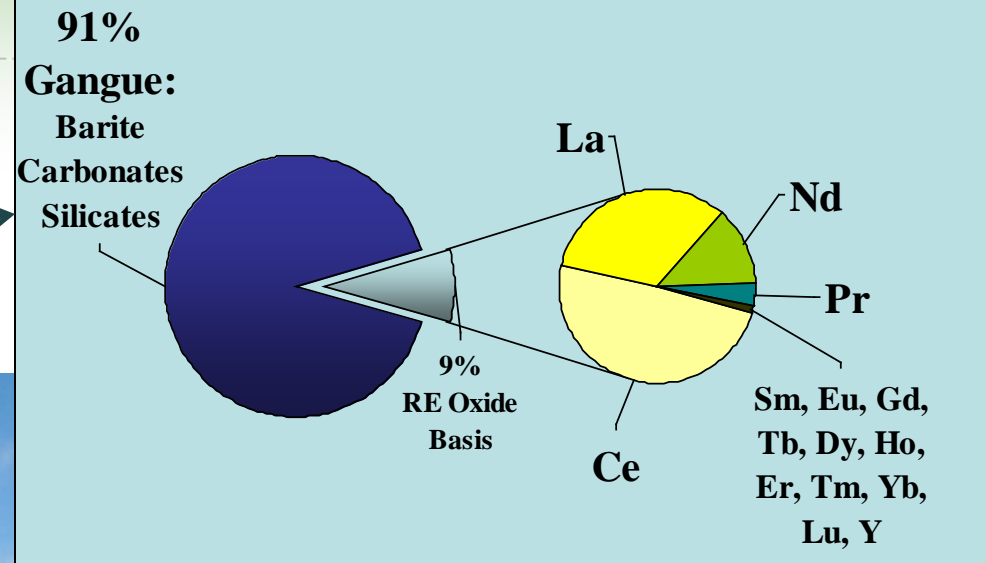
Bastnasite: $\text{RE}-(\text{CO}_3)\text{F}$
3.3 million metric tons:
7-9% REO



Photos: Google Maps

Molycorp Rare Earth Facility

Mountain Pass, CA



Energy

Different Types of Rare Earths

Heavy and Light Rare Earths
are from different Ores

Light Rare Earths

Neodymium – Magnets

Heavy Rare Earths

Dysprosium - High
Temp Magnets

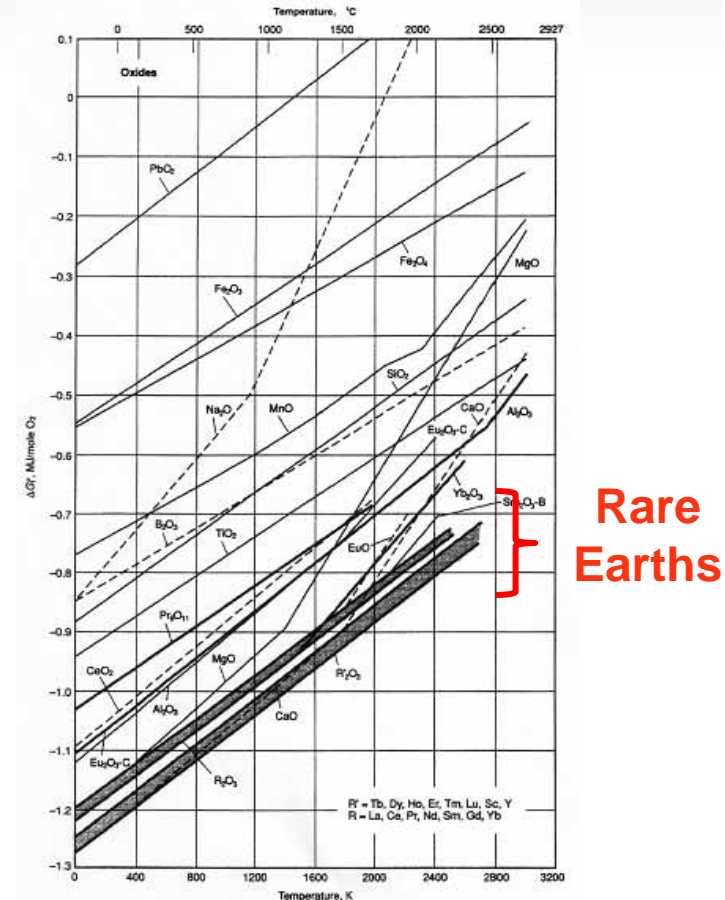
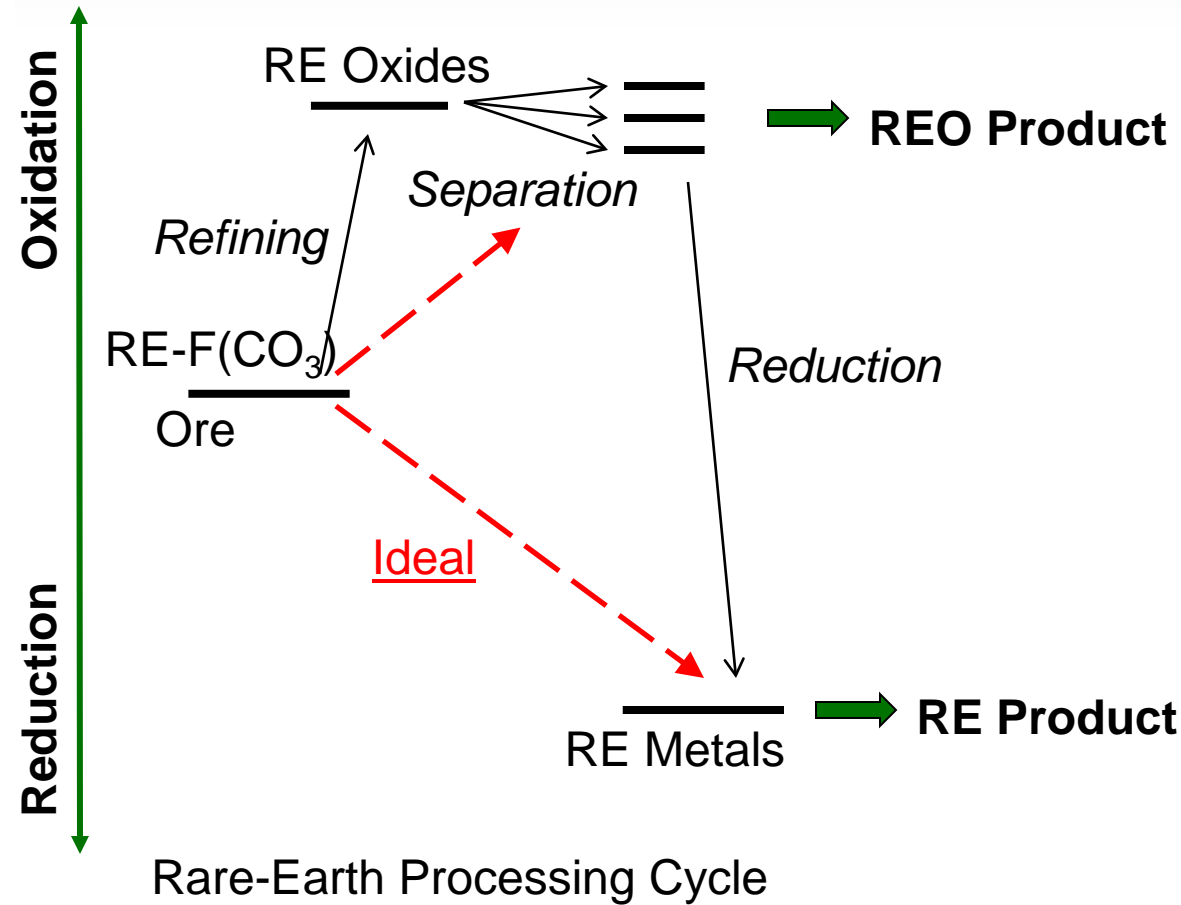
Yttrium – SOFCs and
Phosphors

Terbium – Phosphors

Europium - Phosphors

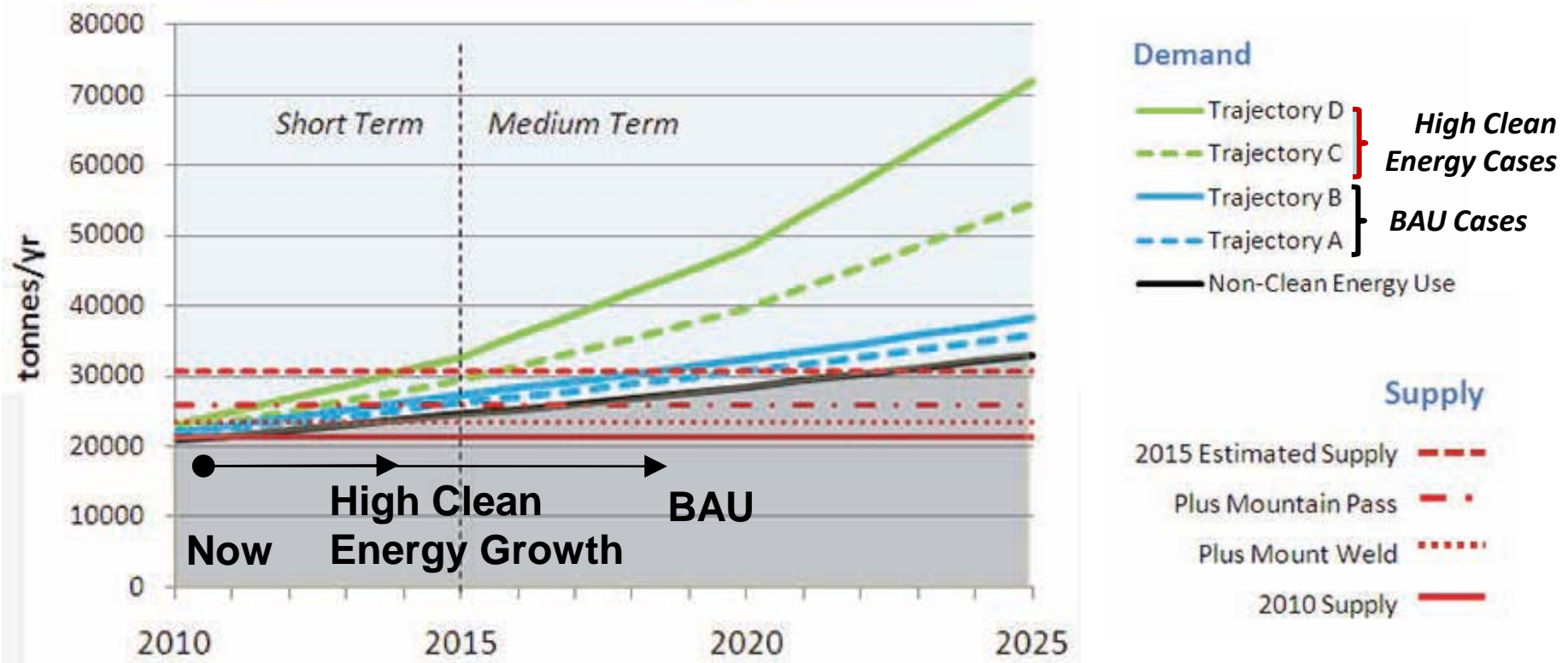
TYPE	LOCATION (S)	LIGHT			MEDIUM				HEAVY							
		Lanthanum (La)	Cerium (Ce)	Praseodymium (Pr)	Neodymium (Nd)	Samarium (Sm)	Europium (Eu)	Gadolinium (Gd)	Terbium (Tb)	Dysprosium (Dy)	Holmium (Ho)	Erbium (Er)	Thulium (Tm)	Ytterbium (Yb)	Lutetium (Lu)	Yttrium (Y)
Currently active:																
Bastnäsite	Bayan Obo, Inner Mongolia	23.0	50.0	6.2	18.5	0.8	0.2	0.7	8.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Xenotime	Lahat, Perak, Malaysia	1.2	3.1	0.5	1.6	1.1	0.0	3.5	0.9	8.3	2.0	6.4	1.1	6.8	1.0	61.0
Rare earth laterite	Xunwu, Jiangxi Province, China	43.4	2.4	9.0	31.7	3.9	0.5	3.0	0.0	0.0	0.0	0.0	0.0	0.3	0.1	8.0
Ion adsorption clays	Longnan, Jiangxi Province, China	1.8	0.4	0.7	3.0	2.8	0.1	6.9	1.3	6.7	1.6	4.9	0.7	2.5	0.4	65.0
Loparite	Lovozerskaya, Russia	28	57.5	3.8	8.8	0.0	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Various	India	23	46	5	20	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Various	Brazil	N.A.														
Possible to come online in the next 5 years:																
Bastnäsite ²²	Mountain Pass, California, United States	33.2	49.1	4.3	12.0	0.8	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Monazite	Mount Weld, Australia	26.0	51.0	4.0	15.0	1.8	0.4	1.0	0.1	0.2	0.1	0.2	0.0	0.1	0.0	0.0
	Eastern coast ²³ , Brazil	24.0	47.0	4.5	18.5	3.0	0.1	1.0	0.1	0.4	0.0	0.1	0.0	0.0	0.0	1.4
Apatite	Nolans bore, Australia	20.0	48.2	5.9	21.5	2.4	0.4	1.0	0.1	0.3	0.0	0.0	0.0	0.0	0.0	0.0
Fergusonite ²⁴	Nechalaco, Canada	16.9	41.4	4.8	18.7	3.5	0.4	2.9	1.8	0.7	0.0	0.0	0.0	0.0	0.0	7.4
Bastnäsite & Parisite	Dong Pao, Vietnam	32.4	50.4	4.0	10.7	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.007
Alanite & apatite	Hoidas Lake, Canada	19.8	45.6	5.8	21.9	2.9	0.6	1.3	0.1	0.4	0.0	0.0	0.0	0.0	0.0	1.3
Trachyte	Dubbo Zirconia, Australia	19.5	36.7	4.0	14.1	2.5	0.1	2.1	0.3	2.0	0.0	0.0	0.0	0.0	0.0	15.8

Rare Earth Oxide and Metal Extraction Process

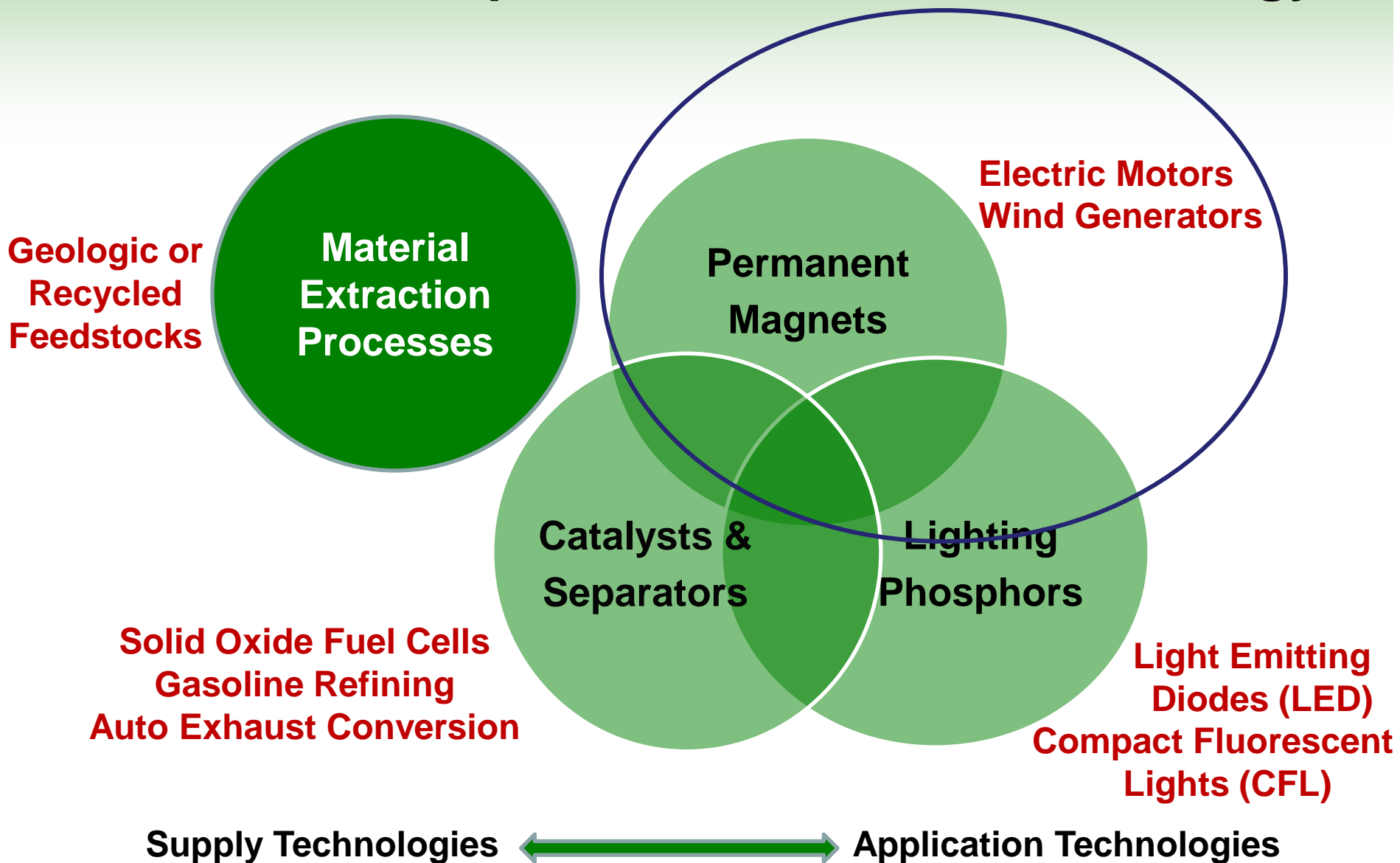


Supply and Demand Scenarios Neodymium (Permanent Magnets)

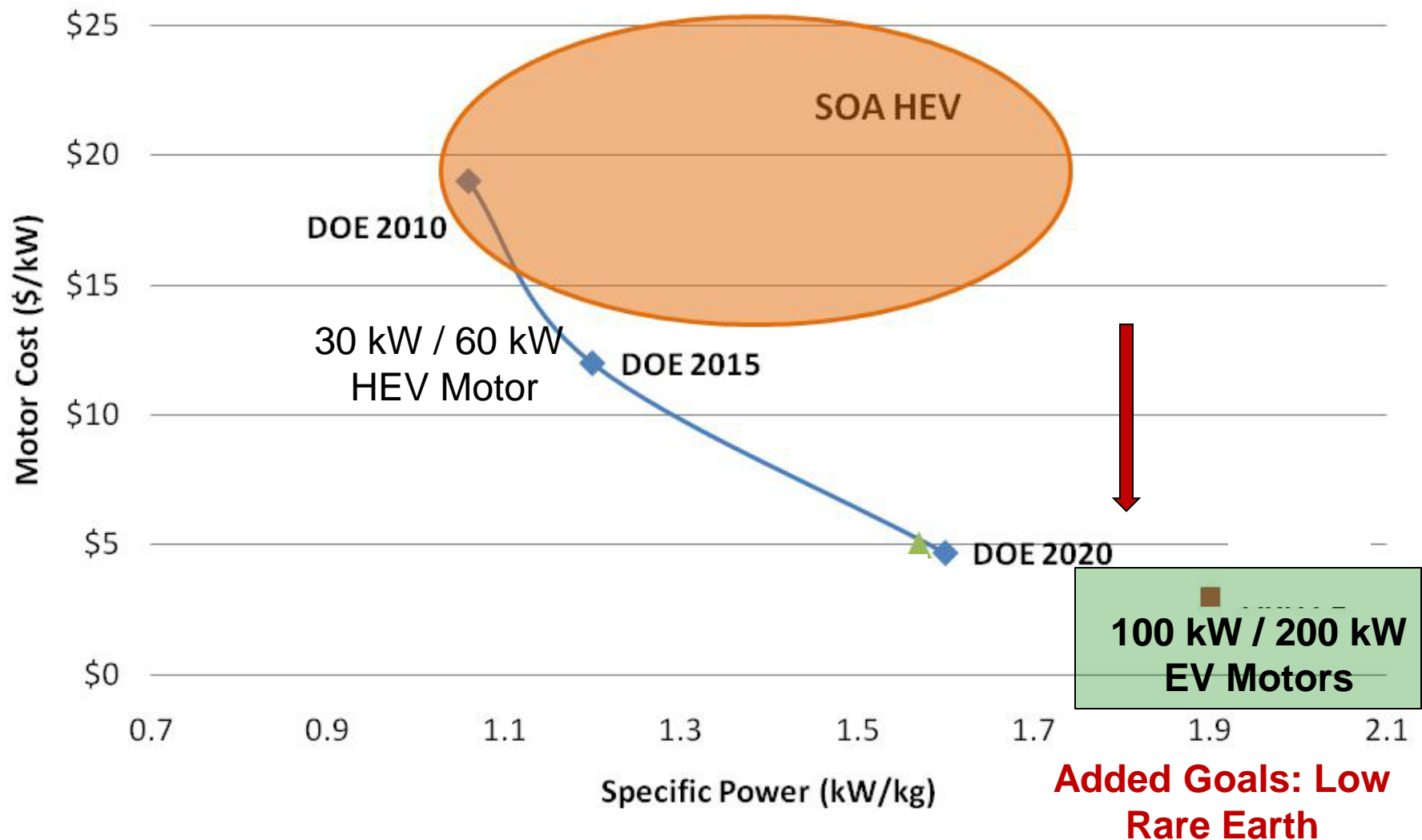
Neodymium Oxide Future Supply and Demand



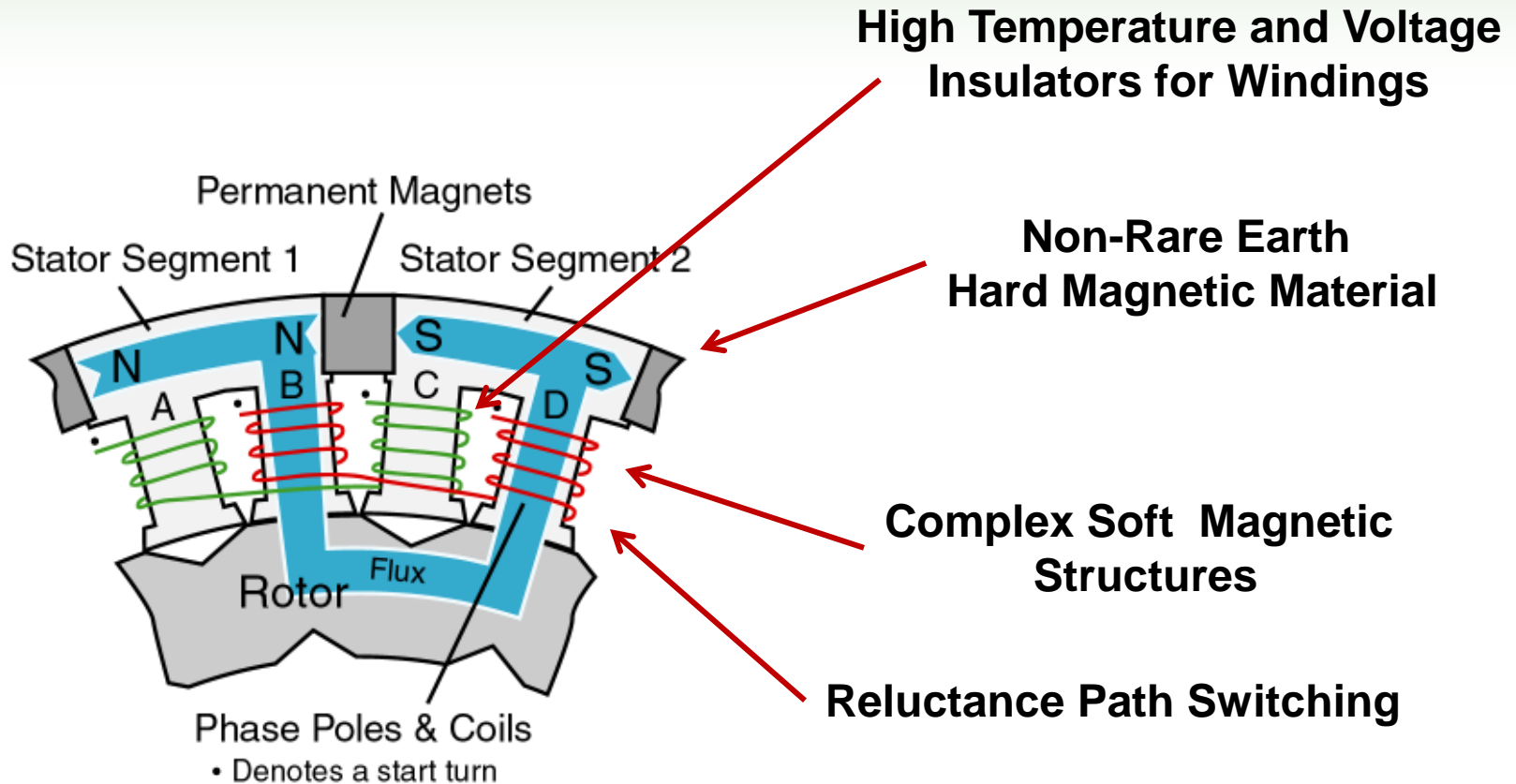
ARPA-E Workshop: Critical Materials Technology



Magnetic Systems: Motors for Electric Vehicle (EV) 2020 Roadmap Goals with Low Rare Earth Content

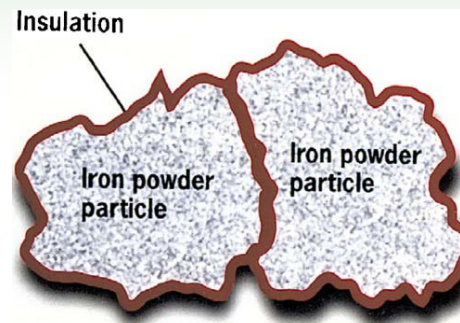
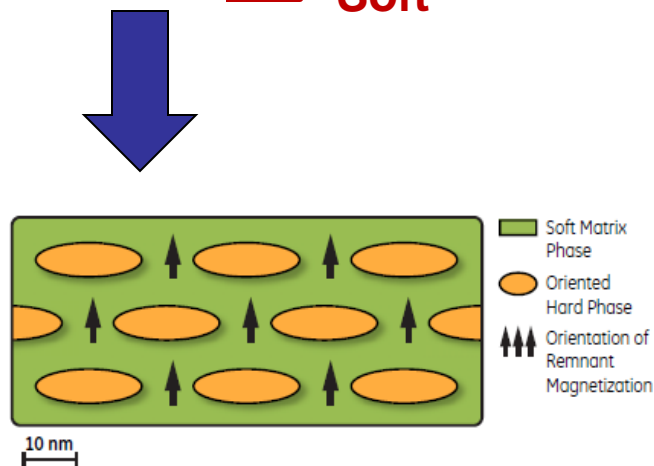
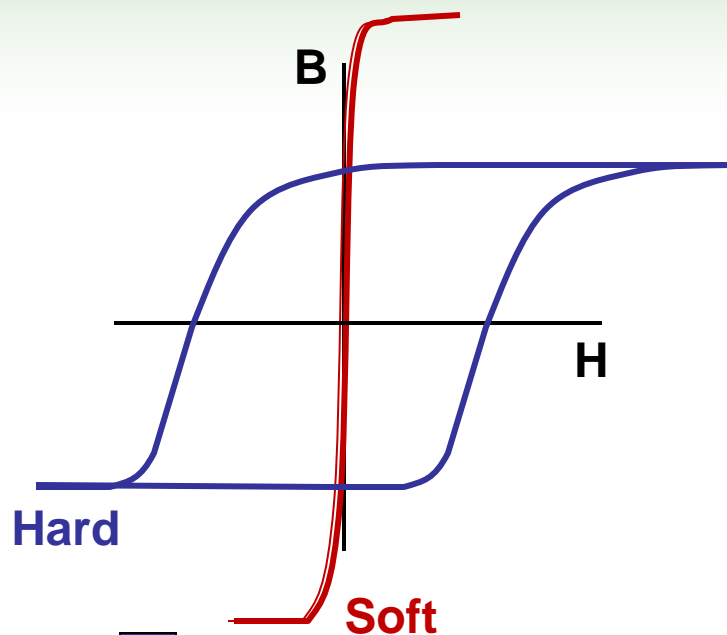


Advanced Electric Motor Concepts



Example: Parallel Path Magnetic Motor Technology

Needed Enabling Magnetic Materials



Soft Magnetic Nanocomposite

High Permeability (Fe, Fe-Si, Fe-Co)

Low Eddy Current Loss

Isotropic Permeability (ideal)

Manufacture-able / Moldable

Enables Novel Structures

Hard Magnetic Nanocomposite

Spring Exchange Coupling

Coercivity of Hard Phase (SmCo, NdFeB)

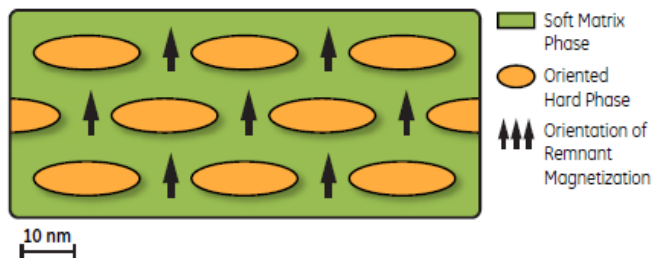
Remnance of Soft Phase (Fe, Fe-Co)

High Energy Density

Reduced Rare Earth Content

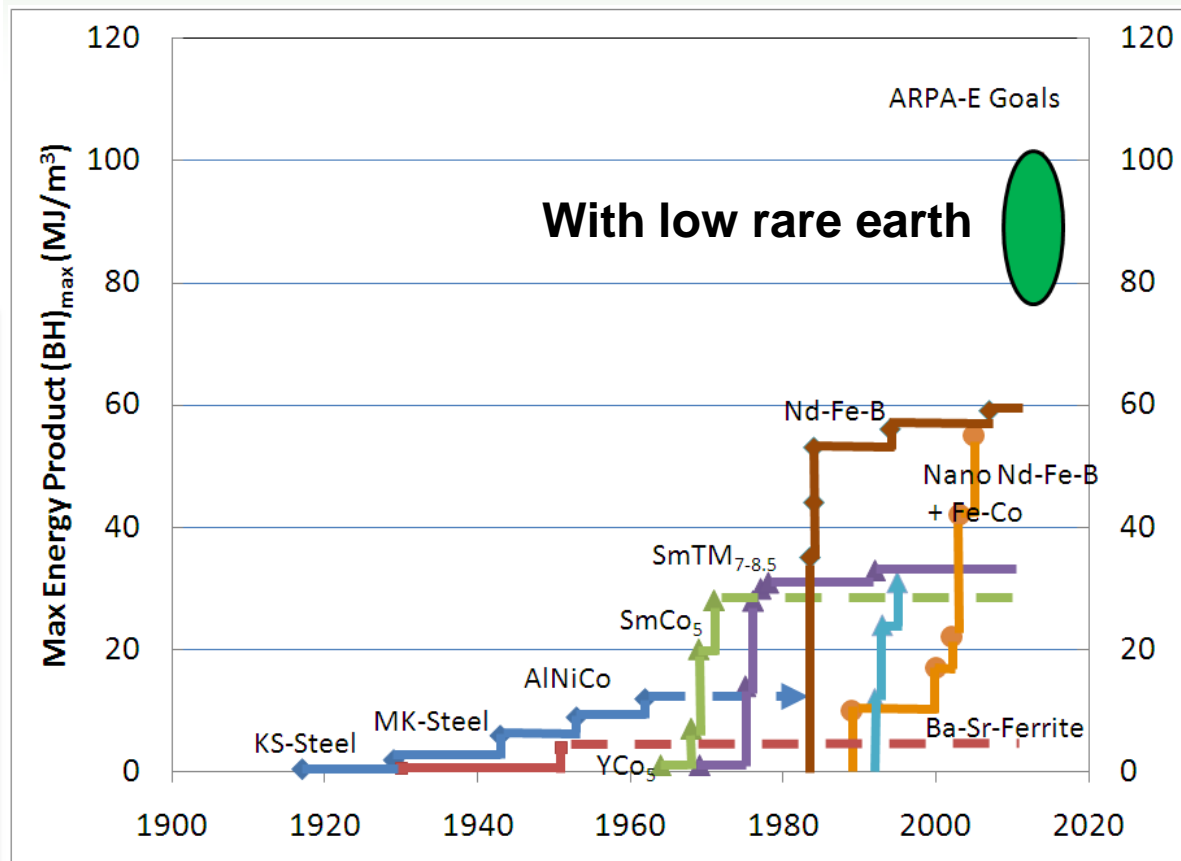
Current: U Del. & GE

Nanocomposite Permanent Magnets



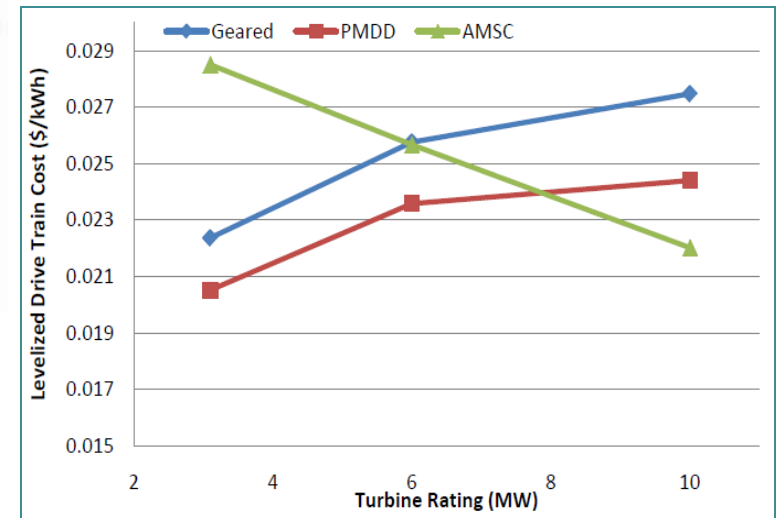
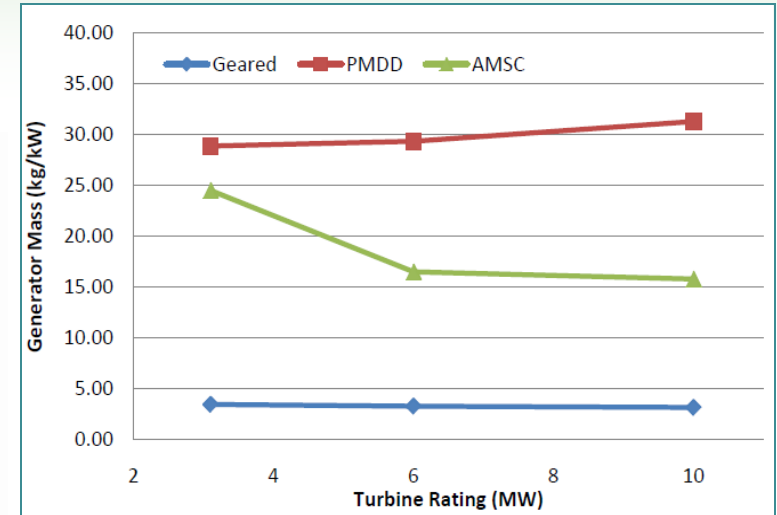
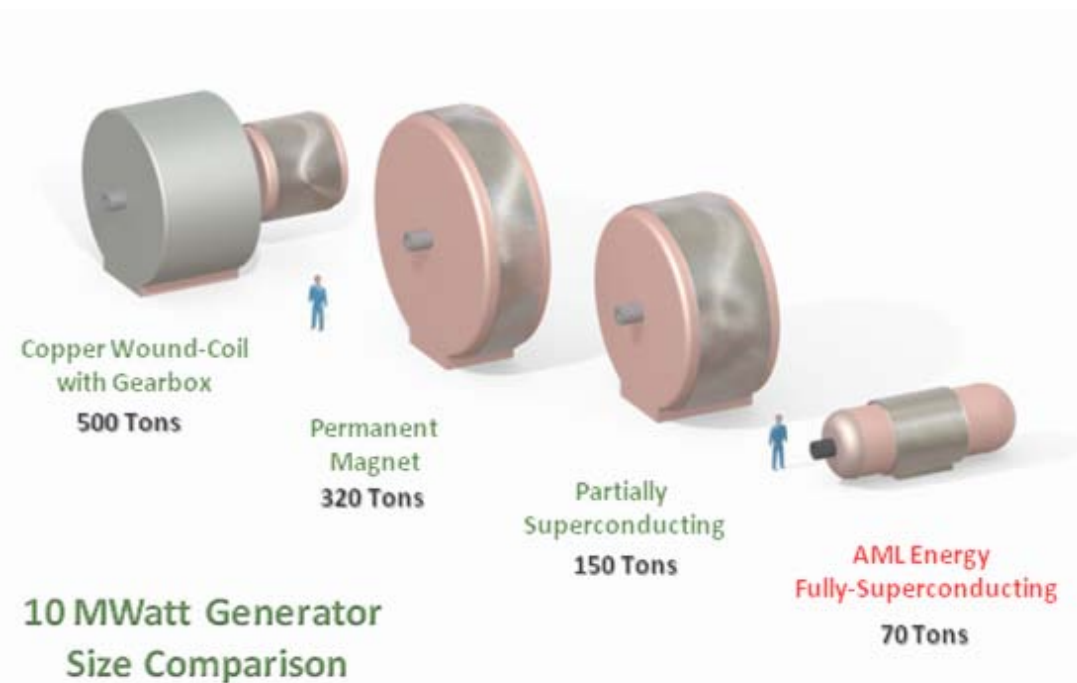
Core@Shell Hard/Soft
Exchange Spring Coupled
Nanocomposite Magnets
with:

- 80 MGOe
(vs 59 MGOe NdFeB)
- 59 MGOe
with 80% less rare earth

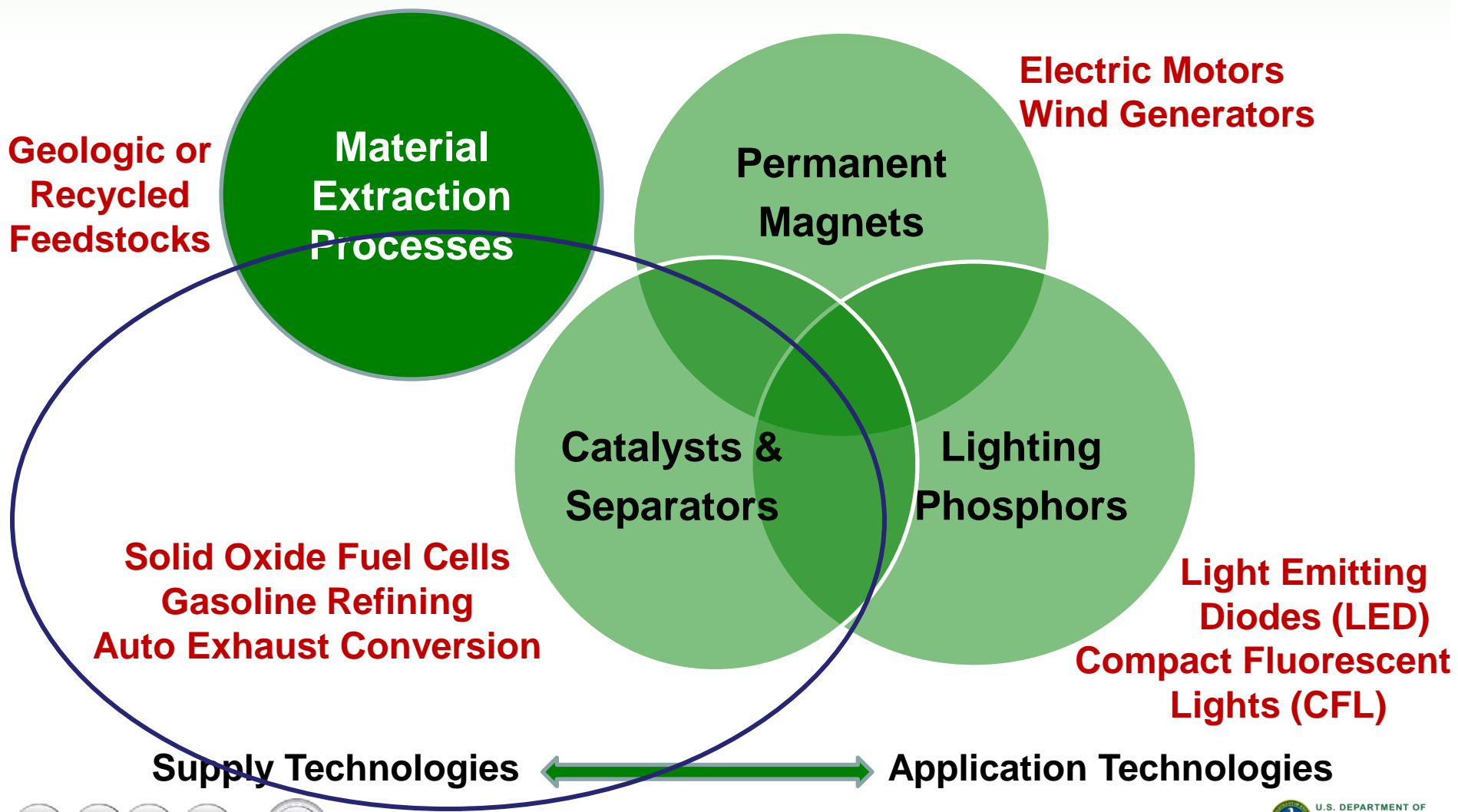


Nanocomposite exchange spring coupled permanent magnets
with high energy product and less rare earths

Large Scale Wind Generator (>10MW) Systems



ARPA-E Workshop: Critical Materials Technology



Catalysts: Fluid Catalytic Cracking

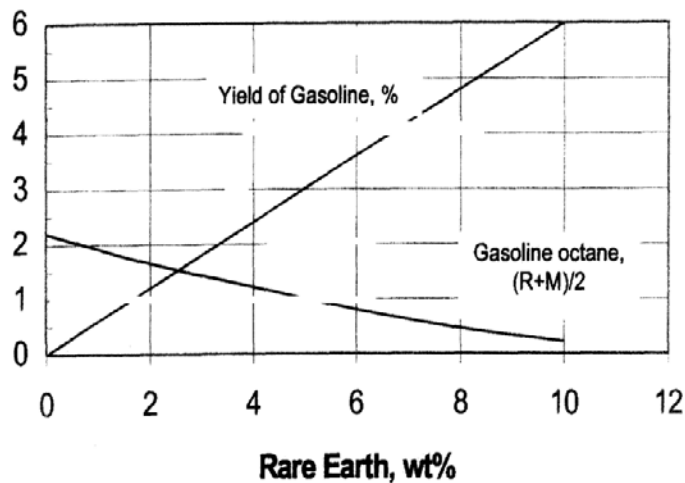
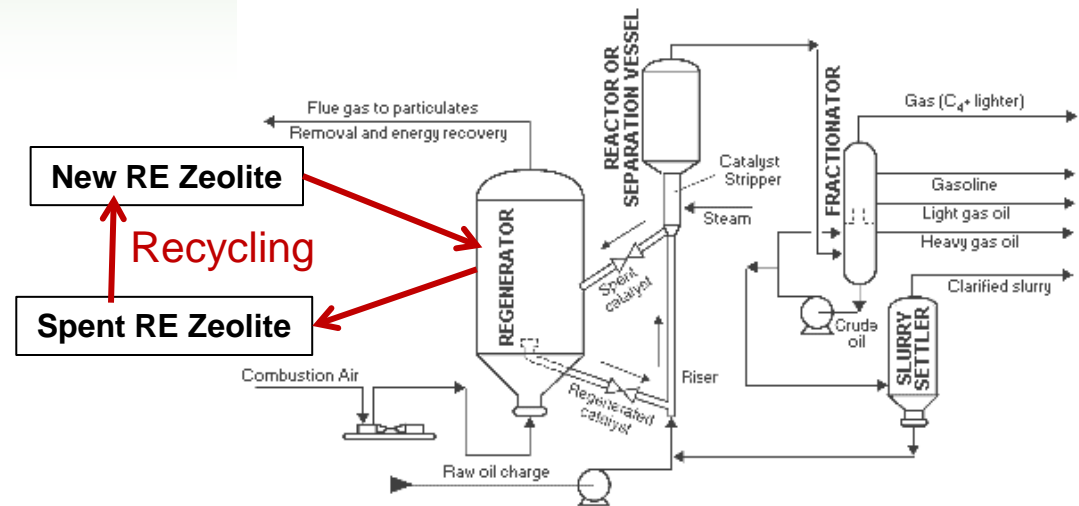
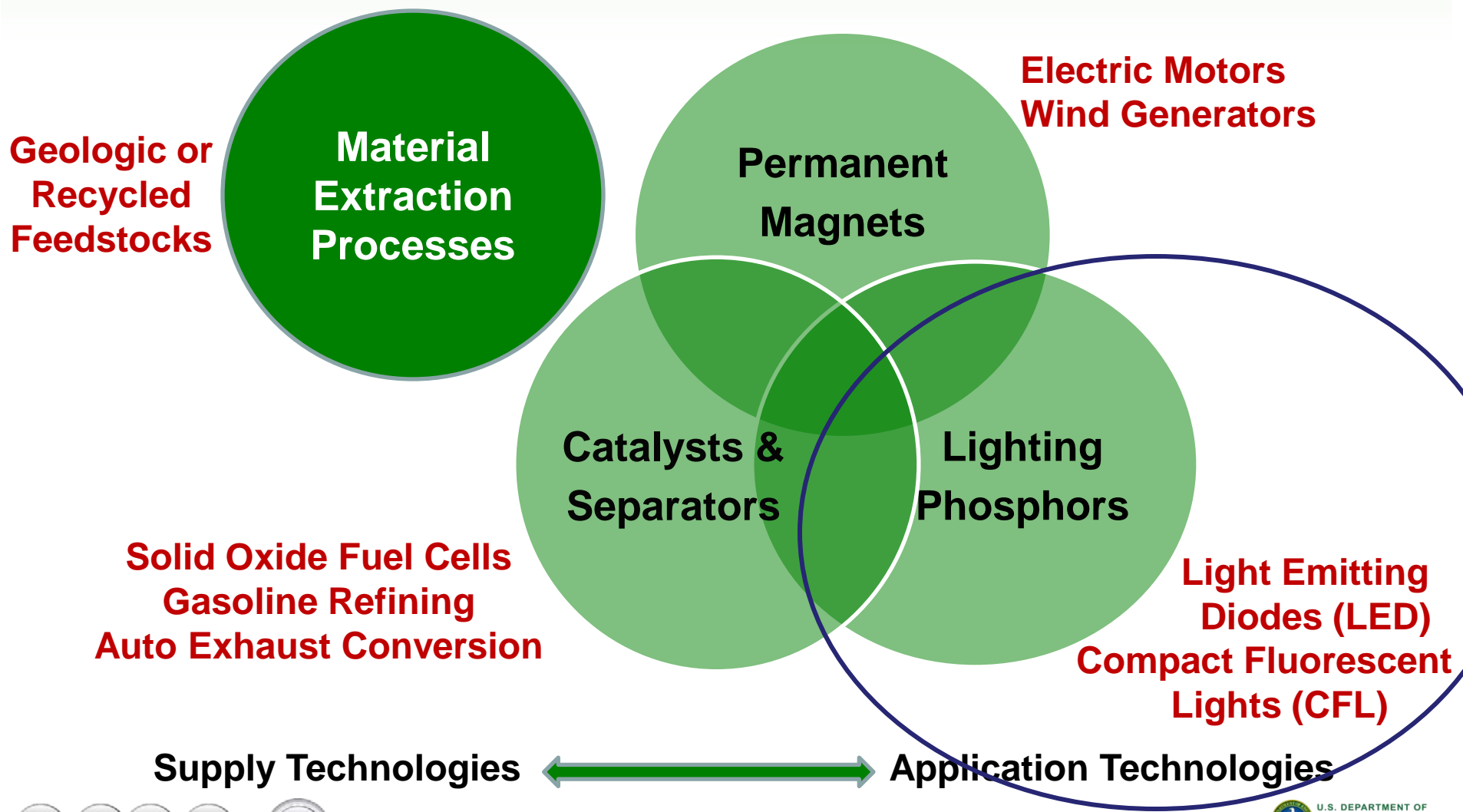


Figure 3-6. Effects of rare earth on gasoline octane and yield.

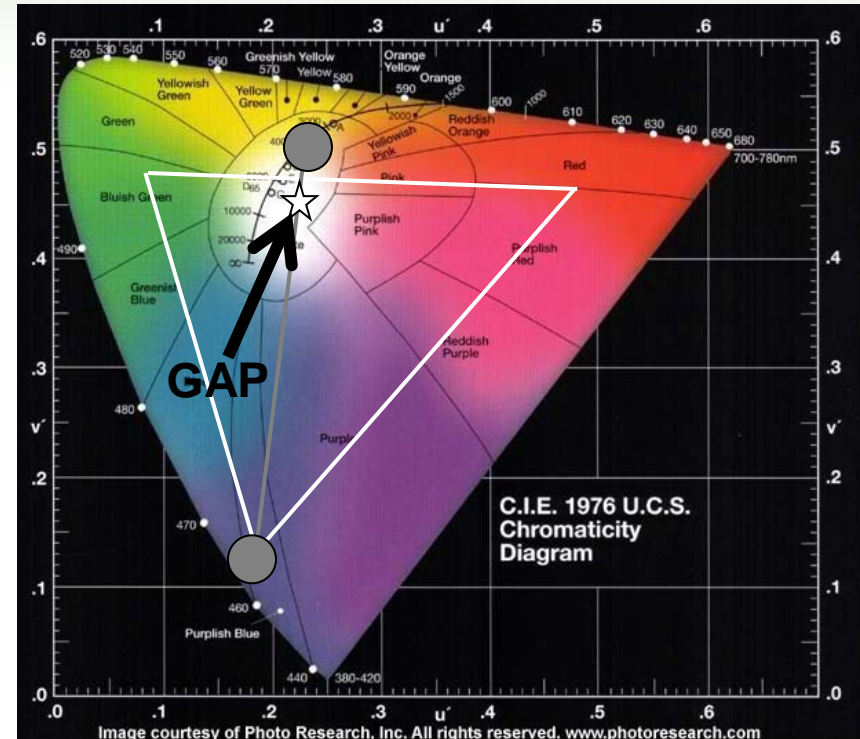
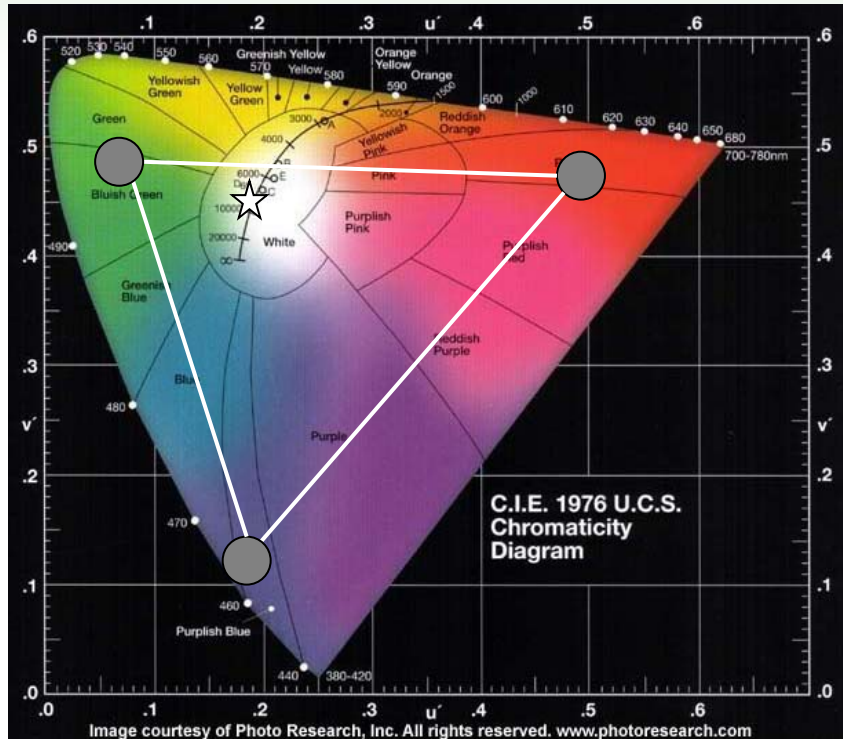
1-2% catalysts replaced per day.
All catalyst replaced every 2 months
due to loss of aluminum.
Old catalyst is landfilled.

Recover Rare-earth content from spent
FCC catalyst could potentially have Impact.

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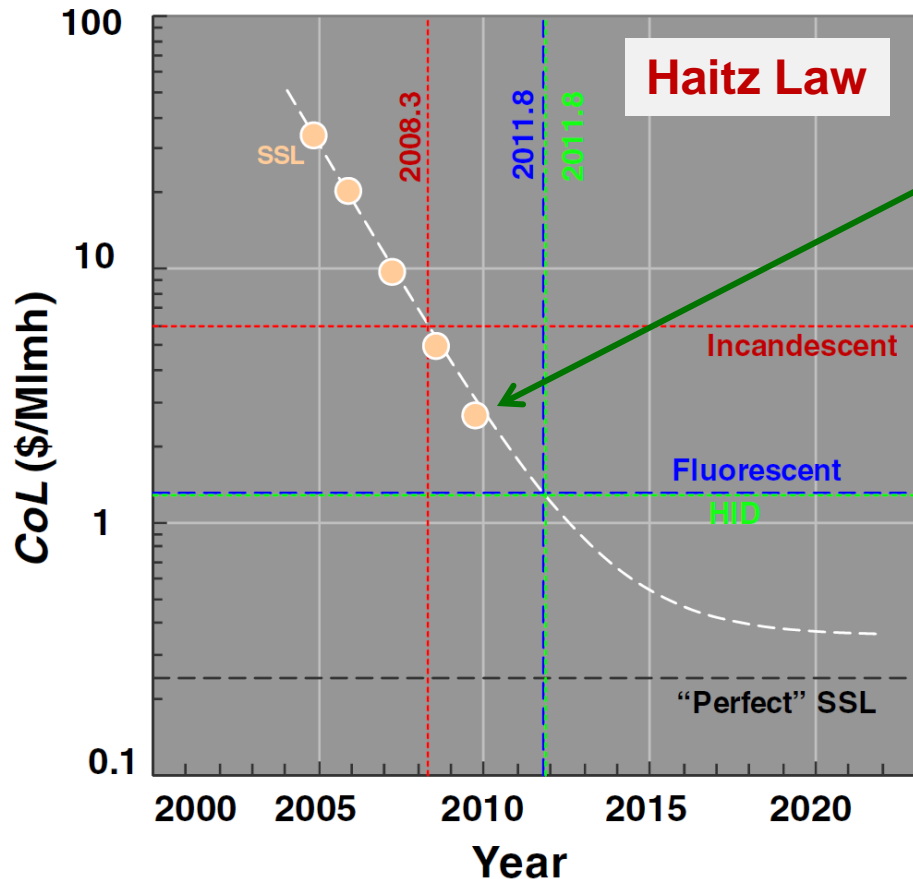


Application: Rare Earth Phosphors for CFLs

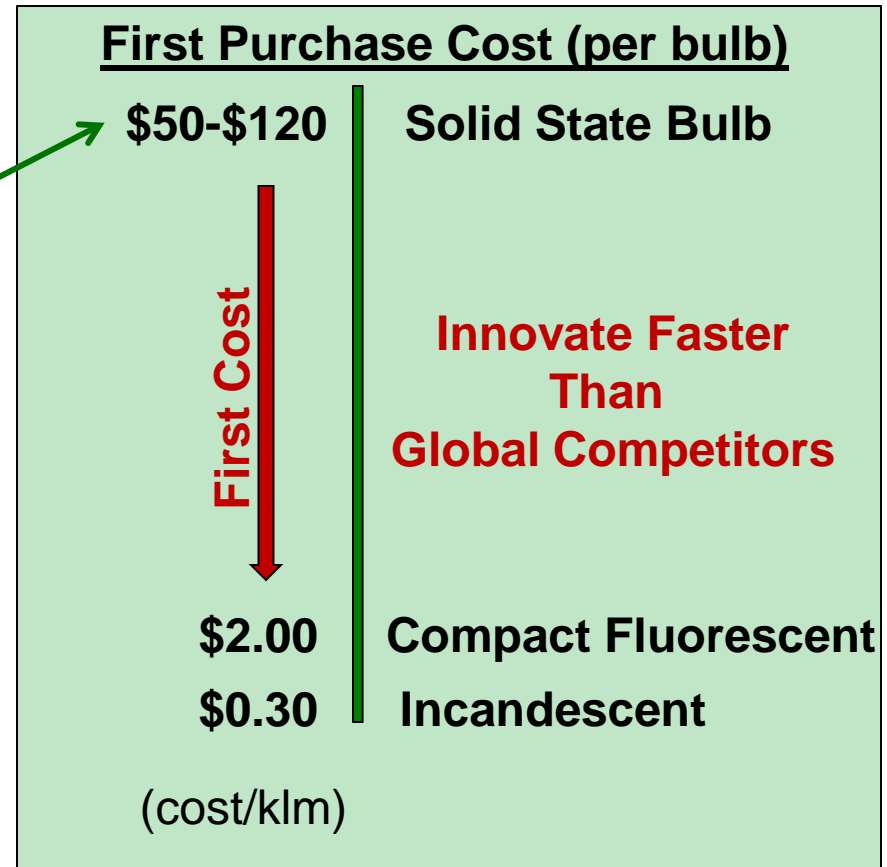


Phosphor	Code	Color	Emission Wavelength	Nature	Rare Earth(s)
$\text{BaMgAl}_{10}\text{O}_{19}:\text{Eu}^{2+}$	BAM	Blue	450 nm	Broad band	Eu
$\text{LaPO}_4:\text{Ce}^{3+}, \text{Tb}^{3+}$	LAP	Green	545 nm	Sharp line	La,Ce,Tb
$\text{Y}_2\text{O}_3:\text{Eu}^{3+}$	YEO	Red	610 nm	Sharp line	Y, Eu

Cost of Lighting (CoL) vs. First Lumen Cost (Bulb)



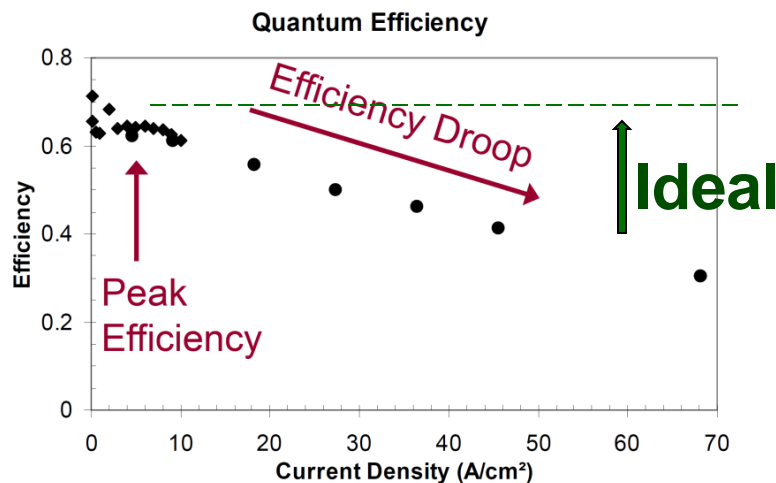
J.Tsao, et.al., *Proc. IEEE* (9/09)



First Purchase Price for Lighting

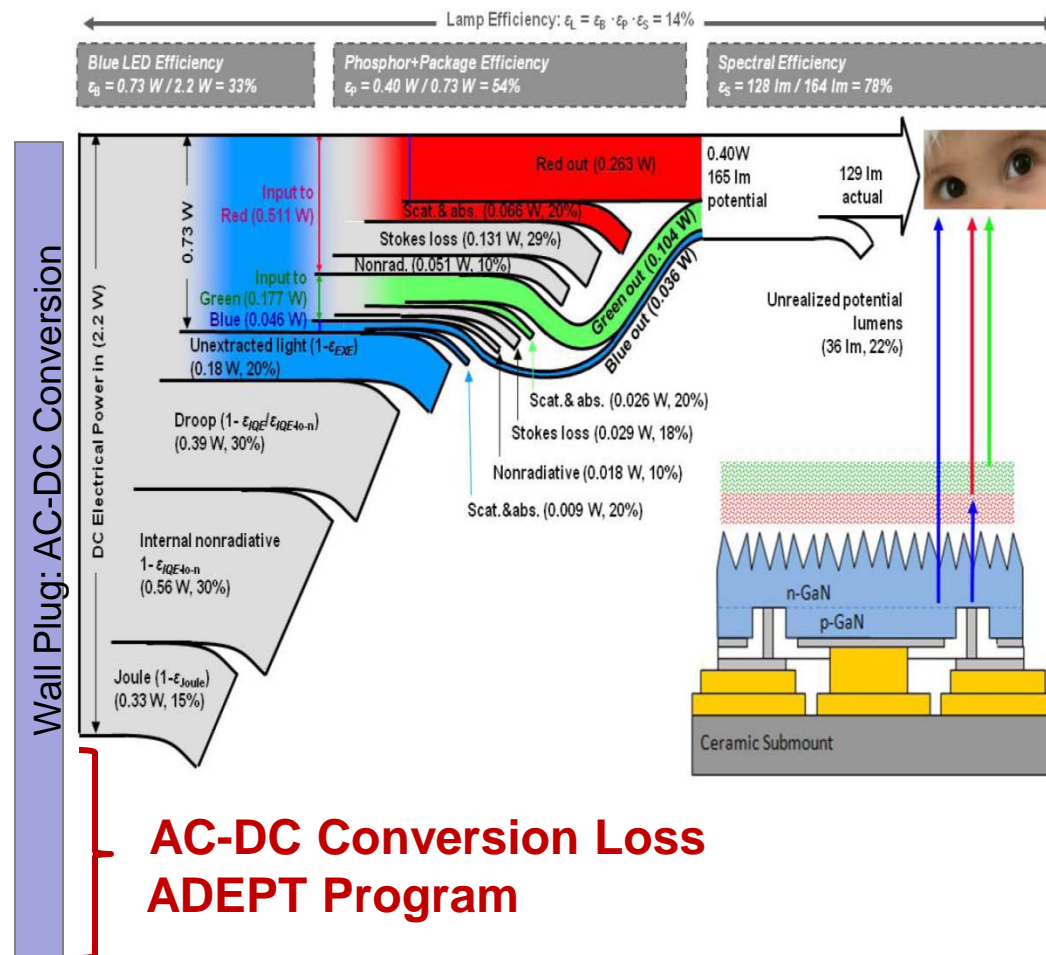


Technical Pathway to Low First Cost LEDs: Eliminate Droop Losses Through Innovation



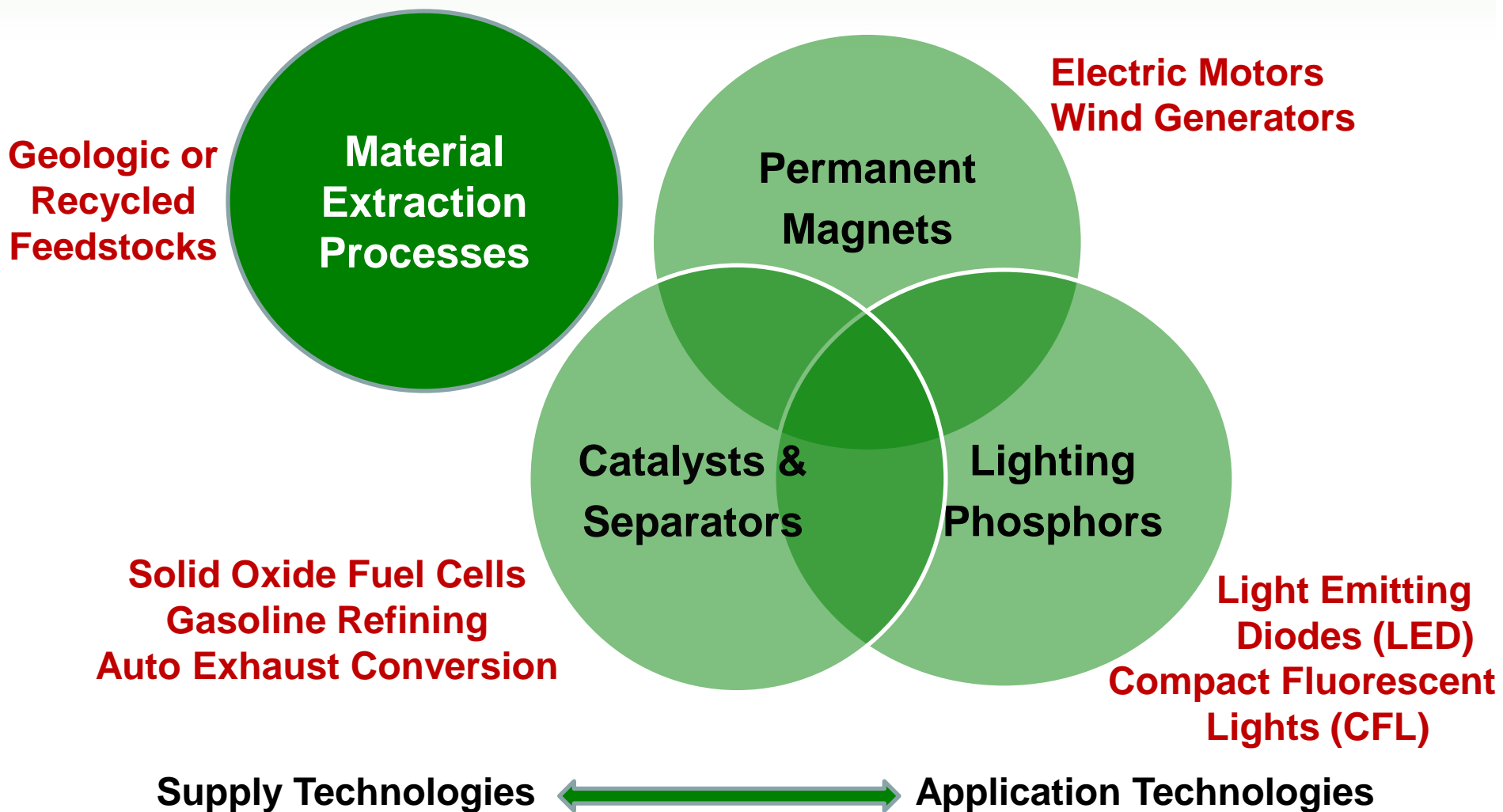
Physical Origins of Droop
 Auger Recombination
 Non-Radiative Defects
 Carrier Overflow from MQWs
 Crystal Polarity

Rare Earth Free Phosphors
Luminescent Nanoparticles
 without Cadmium



J.Tsao, et.al., *Proc. IEEE* (9/09)

Summary: Critical Materials Technology



Questions
